



Queensland University of Technology

**DISCUSSION PAPERS IN ECONOMICS, FINANCE AND
INTERNATIONAL COMPETITIVENESS**

**Tests of the Random Walk Hypothesis for Australian
Electricity Spot Prices: An Application Employing
Multiple Variance Ratio Tests**

Helen Higgs & Andrew Worthington

Discussion Paper No. 123, November 2002

**Series edited by
Associate Professor Andrew Worthington**

ISSN 1324-5910

All correspondence to:

Associate Professor Andrew Worthington
Editor, *Discussion Papers in Economic, Finance and
International Competitiveness*
School of Economics and Finance
Queensland University of Technology
GPO Box 2434, BRISBANE QLD 4001, Australia

Telephone: 61 7 3864 2658
Facsimile: 61 7 3864 1500
Email: a.worthington@qut.edu.au

School of Economics and Finance

Tests of the random walk hypothesis for Australian electricity spot prices: An application employing multiple variance ratio tests

HELEN HIGGS and ANDREW C. WORTHINGTON*

School of Economics and Finance, Queensland University of Technology, Brisbane, Australia

This paper examines whether Australian electricity spot prices follow a random walk. Daily peak and off-peak (base load) prices for New South Wales, Victoria, Queensland and South Australia are sampled over the period July 1999 to June 2001 and analysed using multiple variance ratio tests. The results indicate that the null hypothesis of a random walk can be rejected in all peak period and most off-period markets because of the autocorrelation of returns. For the Victorian market, the off-peak period electricity spot price follows a random walk. One implication of the study is that in most instances, stochastic autoregressive modelling techniques may be adequate for forecasting electricity prices.

I. INTRODUCTION

Over the last two decades an increasing number of developed and developing economies around the world have restructured their electricity markets. Starting with Chile, Argentina and the United Kingdom, and followed by the United States and most members of the European Union, these efforts have entailed a move away from the heavily-regulated publicly or privately-owned, vertically-integrated utilities of the past towards more market-based structures for electricity suppliers in the present and potentially more competitive outcomes for consumers in the future (Crow 2002).

In the past ten years Australia has also been at the forefront of these efforts to introduce competition into the global power industry. Where electricity was once supplied by state government-owned entities that had never operated on a national or even a regional basis, and where interstate connections were weak and regional electricity trade limited, the market is now characterised by the separation of the generation, transmission and distribution functions by company, and by a competitive national electricity market across the majority of

* Correspondence to: Associate Professor A.C. Worthington, School of Economics and Finance, Queensland University of Technology, GPO Box 2434, Brisbane QLD 4001, Australia. Tel. +61 (0)7 3864 2658, Fax. +61 (0)7 3864 1500, email. a.worthington@qut.edu.au.

Australian states and territories. And for the most part, the restructuring and liberalisation of the Australian electricity market has been a success. In evidence, the benefits to the economy of electricity market liberalisation amounted to \$1.5 billion in 2000 alone, labour productivity in the electricity supply industry doubled in the last decade while capital productivity increased by ten percent, and average retail electricity prices are now more than ten percent below the levels of the early 1990s (ABARE 2002).

However, in recent years the pace of electricity reform in Australia has slowed. The target dates for full retail competition have been delayed and each of the five National Electricity Market (NEM) members (NSW, Victoria, Queensland, South Australia and the Australian Capital Territory) are still characterised by separate transmission companies. Full privatisation has occurred only in Victoria. In South Australia private companies manage the state-owned generation, transmission and distribution companies under long-term leases; in the remaining states and territories they remain in government ownership. The dominance of the individual generating companies in each market is also high with the two largest generators accounting for seventy percent of generation in NSW, and in most other states and territories at least fifty percent. The NEM itself is not yet strongly integrated with interstate trade representing only some seven percent of total generation. During periods of peak demand, the interconnectors can become congested and the NEM separates into its regions, promoting price differences across markets and exacerbating reliability problems and the market power of regional utilities. Ongoing challenges remain in implementing efficient transmission pricing with a view to strengthening interconnection as a check on regional market power and extending retail access to all consumers.

Nevertheless, overriding the electricity reform process in Australia has been the ongoing objective that "...the electricity market should be competitive" such that cost of consuming the delivered electricity is as low as economically feasible, but is still sufficient to induce investment in new capacity. In the short run, the market regulations are constructed in such a way that the most efficient generators are dispatched to meet a given level of electricity demand. The lowest market price provided ensures that all generators are at least compensated for any short run marginal costs incurred (ABARE 2002). In the longer run, it is expected that efficient markets will signal a return on investment, through higher prices, that is sufficient to induce further capacity expansion. Competitive investment would then result in additions to generation capacity in such a way that the average cost of meeting electricity demand requirements over time was minimised (ABARE 2002). Accordingly, the benchmark

for efficiency within the national electricity market is competitive market outcomes. By measuring the extent to which actual market prices exceed the prices that would occur in a competitive market, some assessment of the efficiency of pricing is obtained.

Yet the ability of these newly competitive electricity markets to play the role that is ascribed to them depends not only on their efficiency in an economic sense but also on their efficiency in the market sense. If they are to help improve the operation of the electricity market itself in the shorter term, and the capital market in the longer term, then the price formation process is crucial. And more often than not, an assessment of price formation is couched in terms of 'market efficiency'. Under this efficient market hypothesis prices are rationally related to economic realities and incorporate all the information available to the market. In such a market price changes should be serially random (or follow a random walk) and the absence of exploitable excess or abnormal profit opportunities implies that electricity is appropriately priced at its equilibrium level. Such information is also important because it determines the statistical assumptions that underlie price forecasts in these markets.

Of course, there are any number of reasons to believe that competitive outcomes in electricity markets are associated with random (or non-serially correlated) prices changes while non-competitive outcomes are associated with non-random (or serially correlated) price changes. In a competitive electricity market, prices are inherently volatile as demand varies widely both within a day or week and across seasons within a year. Electricity consumption is difficult to predict and the lack of real-time pricing means demand is not very responsive to price changes. Further, the ability to quickly increase production beyond installed capacity is limited, and the high cost of idle capacity and the lack of economical storage, along with the fact that demand and supply must be continuously balanced to meet certain physical supply quality requirements (frequency, voltage and stability) together imply that prices reflect the underlying volatility in the cost of supplying electricity (ABARE 2002). This would suggest that electricity spot prices should at least approximate a random walk.

However, in a non-competitive environment there is every reason to expect that efforts by generation businesses to exercise market power by withholding capacity or by raising prices at which they are willing to supply electricity above their short run marginal cost will be reflected in sustained price increases. For example, the withholding of capacity by generators in California contributed to significant price increases in 2000/01 (Joskow and Kahn 2001) while Robinson and Baniak (2002) found generators in the English and Welsh Electricity Pool had an incentive to raise prices and manipulate volatility in order to benefit

from higher risk premia in the contract market. Wolfram (1999) likewise examined the impact of duopoly power in the British electricity market.

In this paper an attempt is made to examine the informational efficiency of the four state-based regional electricity markets that comprise the Australian National Electricity Market by testing for random walks in the wholesale electricity prices. The paper itself is divided into five main areas. Section II briefly surveys the establishment and operation of the Australian National Electricity Market. Section III provides a description of the data employed in the analysis, while Section IV discusses the methodology employed. The results are dealt with in Section V and Section VI provides a brief conclusion.

II. AUSTRALIAN ELECTRICITY MARKETS

The Australian National Electricity Market (NEM) encompasses electricity generators in the eastern state electricity markets of Australia operating as a nationally interconnected grid. The member jurisdictions of the NEM thus include the three most populous states of New South Wales (NSW) [including the Australian Capital Territory (ACT)], Victoria (VIC) and Queensland (QLD) along with South Australia (SA). The only non-state based member that currently provides output into the NEM is the Snowy Mountains Hydroelectric Scheme (SNO). The SNO is regarded as a special case owing to the complexity of arrangements underlying both its original construction and operating arrangements involving both the state governments of New South Wales and Victoria, as well as the Commonwealth (federal) government. It is intended that the island state of Tasmania will become a member of the NEM pending completion of the Basslink interconnector, which will link Tasmania's Electricity Supply Industry with that of the mainland. The remaining Australian state of Western Australia along with the Northern Territory are unlikely to participate in the NEM in the foreseeable future due to the economic and physical unfeasibility of interconnection and transmission augmentation across such geographically dispersed and distant areas.

The limitations of transfer capability within the centrally coordinated and regulated NEM are indeed one of its defining features. Queensland has two interconnectors that together can import and export 880 MW to and from NSW, NSW can export 850 MW to the Snowy and 3000 MW from the Snowy and Victoria can import 1500 MW from the Snowy and 250 MW from South Australia and export 1100 MW to the Snowy and 500 MW to South Australia. There is currently no direct connector between NSW and South Australia and Queensland is only connected directly to NSW.

The NEM was developed and operates under a number of legislative agreements, memorandums of understanding and protocols between the participating jurisdictions. They include a mechanism for uniformity of relevant electricity legislation across states, implementation of the National Electricity Code (NEC) and the creation of the National Electricity Code Administrator (NECA) and the National Electricity Market Management Company (NEMMCO) to control and implement the NEM. The NECA is the organisation charged with administering the NEC. This entails monitoring participant compliance with the Code and raising Code breaches with the National Electricity Tribunal (IEA: 2001: 132). Other roles of the NECA include managing changes to the NEC and establishing procedures for dispute resolution, consultative, and reporting procedures (NEMMCO, 2001: 28). The NECA also established the Reliability Panel in 1997, in order to “determine power system security and reliability standards, and monitor market reliability” (IEA: 2001: 132).

The market rules that govern the operation of the NEM are embedded in the NEC, which was developed in consultation with government, industry and consumers during the mid-1990s. NEMMCO (2001: 4) summarises the rationale for the thoroughness of the NEC:

The rules and standards of the Code ensure that all parties seeking to be part of the electricity network should have access on a fair and reasonable basis. The Code also defines technical requirements for the electricity networks, generator plant, and customer connection equipment to ensure that electricity delivered to the customers meets prescribed standards.

The NEC required authorisation by the Australian Competition and Consumer Commission (ACCC) to be implemented, as do any changes. Born from the Hilmer microeconomic reforms in the 1990s the ACCC is the peak Australian body aimed at enforcing competition law. To this affect, the ACCC is responsible for administering the Trade Practices Act (1974), which was augmented under the National Competition Policy (NCP) reforms to facilitate access arrangements to network infrastructure and the addition of competitive neutrality provisions, which ensure there can be no discrimination between public and private service providers. Asher (1998: 10) highlights the key change to the Trade Practices Act (1974) under the National Competition Policy reforms as “establishing a third party access regime to cover the services provided by significant infrastructure facilities” (facilities not economically feasible to duplicate and where the access arrangements would be necessary to promote effective competition in upstream or downstream markets). In addition to the administration of this role in regard to market infrastructure, the ACCC is the

organisation responsible for the regulation of the transmission network component of the Australian Electricity Supply Industry. Of the various facets this role encompasses, transmission pricing is the most prominent. This is managed by the ACCC on a revenue cap basis, in an attempt “to constrain monopoly pricing while allowing the business owners a rate of return sufficient to fund network operation and expansion” (ACCC, 2000: 8). In brief, the ACCC’s price cap methodology is (IEA 2001: 137):

The revenue of transmission companies is regulated on the basis of an adjusted replacement value of the assets, known as deprival value, and its weighted cost of capital. The maximum annual revenue allowed to transmission is subject to a “CPI-X” price cap, fixed for a period of at least five years, that reduces transmission charges over time in real terms.

The transmission-pricing role is carried out in conjunction with a service reliability protocol, to ensure quality of service. As noted, changes to the NEC effecting transmission or any other aspect of the market must be authorised by the ACCC. As such the ACCC is responsible for the evaluation of changes to market operations. It is the role of the National Electricity Market Management Company (NEMMCO) to implement and administer changes to market operation.

The National Electricity Market Management Company (NEMMCO) operates the wholesale market for electricity trade between generators and retailers (and also large consumers). From an operational perspective, output from generators is pooled then scheduled to meet demand. The IEA (2001: 134) summarises the core elements as follows:

The National Electricity Market is a mandatory auction in which generators of 30 MW [megawatts] or more and wholesale market customers compete. Generators submit bids consisting of simple price-quantity pairs specifying the amount of energy they are prepared to supply at a certain price. Up to ten such pairs can be submitted per day. In principle, these bids are firm and can only be altered under certain conditions. Generator bids are used to construct a merit order of generation. Customer bids are used to construct a demand schedule. Dispatch minimises the cost of meeting the actual electricity demand, taking into account transmission constraints for each of the five regions in which the market is divided... There are no capacity payments or any other capacity mechanisms.

The two key aspects required for the pool to operate are a centrally coordinated dispatch mechanism and operation of the ‘spot market’ process. As the market operator, NEMMCO coordinates dispatch to “balance electricity supply and demand requirements” (NEMMCO,

2001: 3), which is required because of the instantaneous nature of electricity, and the spot price is then “the clearing price [that] matches supply with demand” (NEMMCO, 2001: 3).

The pool rules dictate that generators in the NEM with a capacity greater than 30MW are required to submit bidding schedules (prices for supplying different levels of generation) to NEMMCO on a day before basis. Separate capacity schedules are submitted for each of the 48 half-hour periods of the day. As a result, the industry supply curve (also called a bid stack) may be segmented to a maximum extent of ten times the number of generators bidding into the pool. NEMMCO determines prices every five minutes on a real time basis. This is achieved by matching expected demand in the next five minutes against the bid stack for that half-hour period. The price offered by the last generator to be dispatched (plant are dispatched on a least-cost basis) to meet total demand sets the five-minute price. The price for the half-hour trading period (or pool price) is the time-weighted average of the six five-minute periods comprising the half-hour trading period. This is the price generators receive for the actual electricity they dispatch into the pool, and is the price market customers pay to receive generation in that half hour period.

TABLE 1. *Generator offer prices and total electricity demand per half-hour*

Generator	Generator Offer Prices (half-hour)	Time	Total Demand (MW)
6	\$40/MWh	12:05pm	290
5	\$38/MWh	12:10pm	330
4	\$37/MWh	12:15pm	360
3	\$35/MWh	12:20pm	410
2	\$33/MWh	12:25pm	440
1	\$32/MWh	12:30pm	390

An illustration of spot market pricing in the NEM is drawn from NEMMCO (1998: 12). Table 1 contains offer prices for six generators (in megawatt hours) and demand information (in megawatts) for the six five-minute dispatch periods in the 12:30 trading interval. Assuming each of these generators has 100 MW (megawatts) of capacity, Figure 1 graphically analyses the least cost dispatch for these five-minute intervals. For example, at 12:05 total demand is 290 MW and to meet this demand the full capacity of the lowest priced generators 1 (\$32 MWh) and 2 (\$33 MWh) and most of the capacity of generator 3 (\$35 MWh) is required. The marginal price for this five-minute interval is then \$35 MWh. This information, along with the remaining five-minute intervals until 12:30, is tabulated in Table

2, which shows the marginal price for each five-minute interval as a result of the plant dispatch mix, which is primarily dependant on the level of demand. The pool price for the 12:30 trading interval is the average of these six five-minute marginal prices.

FIGURE 1. *Least cost dispatch and generator utilisation*

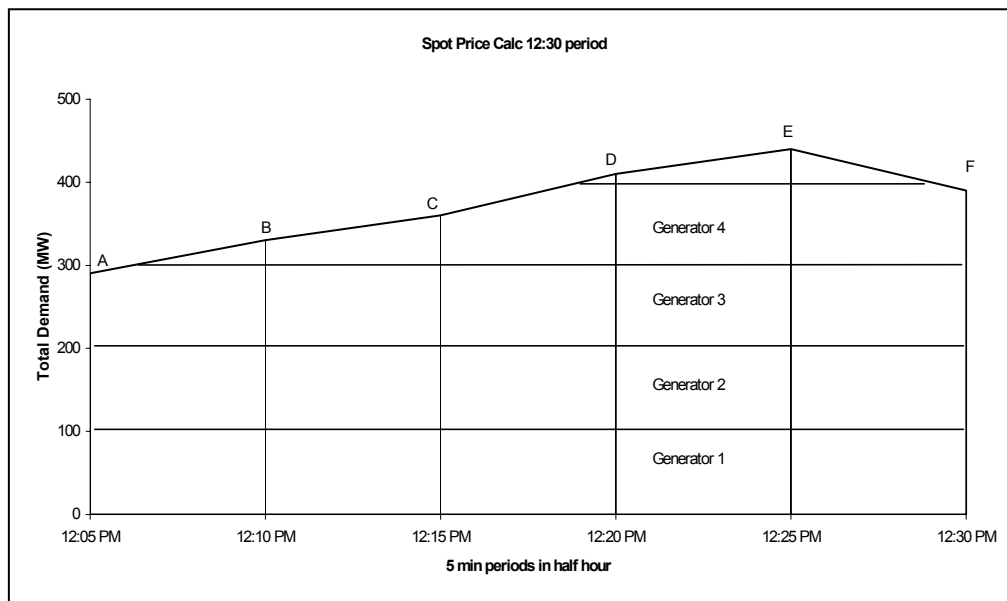


TABLE 2. *Dispatch of generation and spot price calculation*

Graph point price	Dispatch \$/MWh	Time demand	Total (MW)	Scenario
Point A	35	12:05pm	290	Generators 1 & 2 are fully utilised. Generator 3 is partially utilised.
Point B	37	12:10pm	330	Generators 1,2 & 3 are fully utilised. Generator 4 is partially utilised.
Point C	37	12:15pm	360	Generators 1,2 & 3 are fully utilised. Generator 4 is partially utilised.
Point D	38	12:20pm	410	Generators 1,2, 3 & 4 are fully utilised. Generator 5 is partially utilised.
Point E	38	12:25pm	440	Generators 1,2, 3 & 4 are fully utilised. Generator 5 is partially utilised.
Point F	37	12:30pm	390	Generators 1,2 & 3 are fully utilised. Generator 4 is partially utilised.

The spot price is calculated as: $(\$35/\text{MWh} + \$37/\text{MWh} + \$37/\text{MWh} + \$38/\text{MWh} + \$38/\text{MWh} + \$37/\text{MWh}) / 6 = \$37/\text{MWh}$

The spot pricing procedure, while bringing balance between supply and demand, can expose participants to significant variation. This is owing to the dependence of the pool process on generator bidding strategies [for instance, Brennan et al. (1998) highlight the potential for holders of large generating portfolios to bid non-competitively in order to exercise market power] and the impact of the complex interaction of supply and demand factors on pricing. As such the spot price can be volatile, leading to large financial exposure. The occurrence of various phenomenon in the NEM have seen instances of high spot prices, and in some cases the maximum price cap for the NEM (Value of Lost Load) has been triggered.

Events in the past, which have had a tendency to drive NEM prices toward the upper end of the price spectrum, are of three types. First, prices can increase dramatically when a generation plant ‘trips’ or ‘falls over’, rendering it inoperable and forcing the plant’s contributed capacity to be removed from the bid stack. This is particularly the case if the plant provides base load output. Secondly, abnormal environmental temperatures drive demand up as customers increase demand for cooling or heating technology. Higher demand requires more generation to balance the system, which means plant bidding in at a higher price level on the least-cost merit order are sequentially dispatched to meet the additional demand. Third, technical constraints or faults with the systems design can also lead to higher prices. These three instances combined to cause an electricity supply crisis for Victoria in February 2000, as profiled by the IEA (2001: 123):

The Victorian outages reflected a combination of unusual circumstances, including an industrial dispute, which had taken around 20 per cent of generating capacity off line, two unplanned generator outages, and an extremely high peak demand caused by a heat wave across southeastern Australia. The situation was exacerbated by Victorian government intervention to introduce a price cap and establish consumption restrictions, which prolonged the shortages and distorted market responses...The mandatory consumption restrictions introduced by the Victorian government over six days lowered demand in Victoria and had the perverse effect of electricity flowing from Victoria into New South Wales and South Australia while the restrictions were in place.

The illustration of NEMMCO’s dispatch and spot pricing methodology highlights the inherent volatility of the spot price, which can lead to large variations in financial exposure. This is owing to the dependence of the pool process on both generator bidding strategies and the impact of the complex interaction of supply and demand factors on pricing.

III. DESCRIPTION AND PROPERTIES OF THE DATA

The data employed in the study are wholesale prices for electricity encompassing the period from 1 July 1999 to 30 June 2001. All price data is obtained from the National Electricity Market Company (NEMMCO) originally on a half-hourly basis representing 48 trading intervals in each 24-hour period. Following Lucia and Schwartz (2001) a series of daily arithmetic means is drawn from the trading interval data. Although such treatment entails the loss of at least some ‘news’ impounded in the more frequent trading interval data, daily averages play an important role in electricity markets, particularly in the case of financial contracts. For example, the NSW and Victorian base and peak load electricity futures contracts traded on the Sydney Futures Exchange (SFE) from 1999 to 2002 were settled against the arithmetic mean of half hourly spot prices in a given contract month. Moreover, De Vany and Walls (1999a; 1999b) and Robinson (2000) both employ daily spot prices in their respective analyses of the western United States and United Kingdom spot electricity markets.

Table 1. *Descriptive statistics of peak and off-peak spot prices in Australian regional markets, 1999 - 2001*

Statistics	Peak period prices				Off-peak period prices			
	NSW	VIC	QLD	SA	NSW	VIC	QLD	SA
Mean	41.1351	47.0696	59.3459	81.2360	26.7935	27.6042	28.1153	40.1999
Median	30.7717	30.5916	40.5845	49.2485	23.3558	21.0521	22.4447	31.6163
Maximum	585.3686	1658.6050	1078.3920	1880.7390	292.4489	1133.9540	1175.5260	862.1242
Minimum	13.3610	4.2003	16.1152	11.3086	9.6137	6.1663	13.1747	11.8490
Std. Dev.	49.1807	94.1586	75.5536	165.8283	17.6442	48.6029	46.7401	44.8984
Skewness	7.4035	11.8212	7.3861	7.4107	7.9648	18.4743	20.8426	11.3711
Kurtosis	70.0879	178.7824	80.3146	63.4598	104.6152	394.0806	500.9244	177.0935
CV	1.1956	2.0004	1.2731	2.0413	0.6585	1.7607	1.6624	1.1169
J-B	102660	684220	134757	84282	322231	4700002	7604420	938900
J-B <i>p</i> -value	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Observations	522	522	522	522	731	731	731	731

Notes: Prices are in Australian dollars per megawatt-hour; peak period encompasses Mondays to Fridays 7:00 to 21:00, off-peak period encompasses Monday to Fridays before 7:00 and after 21:00 plus Saturday and Sunday, J-B–Jarque-Bera test statistic; NSW–New South Wales, VIC–Victoria, QLD–Queensland, SA–South Australia; CV–Coefficient of variation.

In order to highlight the different price formation processes in the peak and off-peak period spot electricity markets, two separate daily average price series are constructed for each regional market. The peak period series is formed from the half-hourly trading intervals Monday to Friday from 7:00 to 21:00 hours resulting in 522 week day observations. The off-peak period encompasses the remaining Monday to Friday half-hourly trading intervals along with Saturday and Sunday. This results in a longer continuous series of 731 daily

observations. Categorisation of peak and off-peak (or base load) period prices in this manner is identical to that employed in the NEM and as specified in the Sydney Futures Exchange Corporation Limited/d-cypha Limited (a subsidiary of Transpower Limited – owner and operator of the New Zealand national electricity grid) electricity strips for New South Wales, Victoria, Queensland and South Australia.

Figure 2. Graph of logarithm of peak spot prices in Australian regional markets, 1999 - 2001

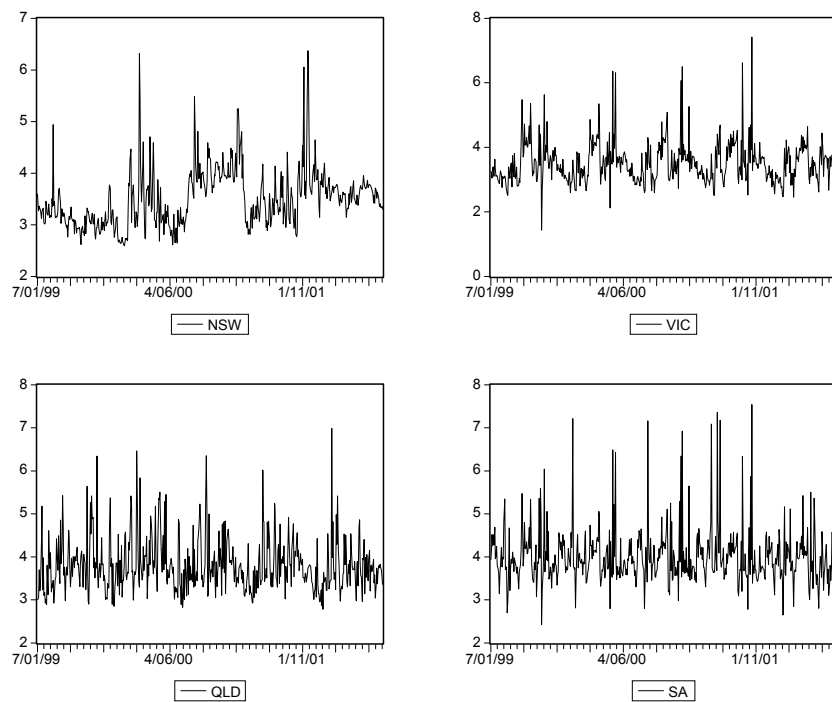
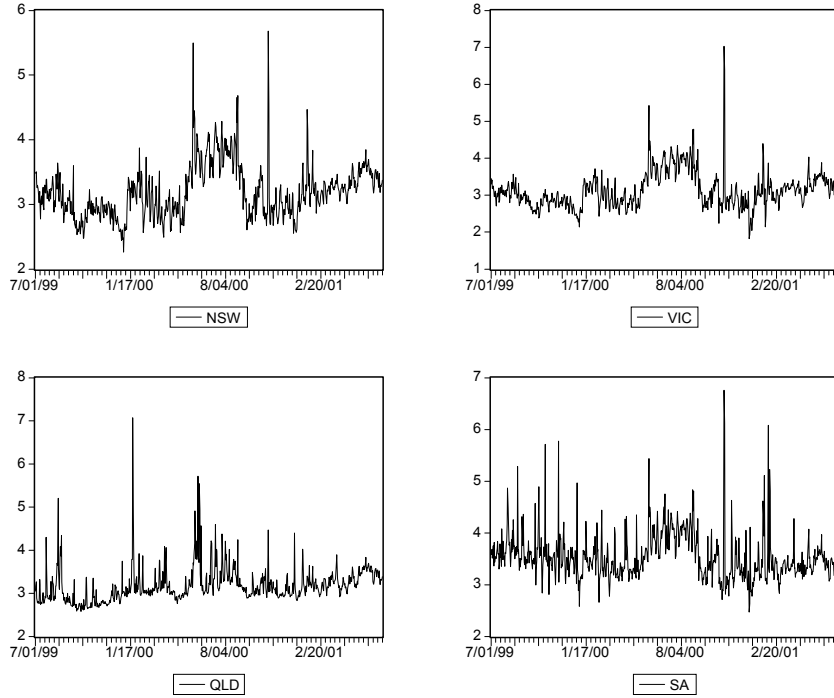


Table 3 presents the summary of descriptive statistics of the daily peak and off-peak period spot prices for the four regional electricity markets. Samples means, medians, maximums, minimums, standard deviations, skewness, kurtosis and the Jacque-Bera statistic and p -value are reported. Figures 2 and 3 graph the logarithm of the daily peak and off-peak period prices over the period selected. Within the period examined, the highest peak spot prices are in Queensland (QLD) and South Australia (SA) averaging \$59.35 and \$81.24 per megawatt-hour respectively. The lowest peak period prices are in New South Wales (NSW) and Victoria (VIC) with average spot prices of \$41.14 and \$47.07 respectively. The standard deviations of spot prices range from \$49.18 (NSW) to \$165.83 (SA). Of the four markets, NSW and QLD are the least volatile with standard deviations of \$49.18 and \$75.55 respectively, whereas VIC and SA are the most volatile with standard deviations of \$94.16 and \$165.83. According to the coefficient of variation, which measures the standard deviation relative to the mean, the peak period prices for VIC and SA are more variable than NSW and QLD. The distributional properties of the spot price series generally appear non-normal. All

spot electricity prices in the peak period are positively skewed, and with kurtosis exceeding three can be represented by a leptokurtic distribution. The calculated Jaque-Bera statistic and corresponding p-value in Table 1 are used to test the null hypothesis that the distribution for the daily average peak spot electricity prices is normally distributed. All p-values are smaller than the 0.01 level of significance indicating that peak period spot electricity prices cannot be approximated by a normal distribution. The off-peak spot prices range from \$26.79 (NSW) to \$40.20 (SA) per megawatt-hour. In general, the off-peak prices are relatively lower than the peak prices for each electricity market, and are also less volatile with standard deviations ranging from \$17.64 (NSW) to \$48.60 (VIC). And similarly to peak period prices, the distributional properties for all regional markets are non-normal.

Figure 2. Graph of logarithm of off-peak spot prices in Australian regional markets, 1999 - 2001



IV. EMPIRICAL METHODOLOGY

Consider the following random walk with drift process:

$$p_t = p_{t-1} + \beta + \varepsilon_t \quad (1)$$

or

$$r_t = \Delta p_t = \beta + \varepsilon_t \quad (2)$$

where p_t is the natural logarithm of the electricity spot price, β is an arbitrary drift parameter, r_t is the change in electricity prices and ε_t is a random disturbance term satisfying $E(\varepsilon_t) = 0$ and $E(\varepsilon_t \varepsilon_{t-g}) = 0$, $g \neq 0$, for all t . The random walk hypothesis implies that the residuals are

both uncorrelated and possess a unit root; thereby providing two alternative testing procedures. In the case of the latter, unit root tests focus on establishing whether a series is difference stationary or trend stationary. However, it is well known that unit root tests have very low power and often fail to detect some departures from random walks (Smith et al 2002: 479). An alternative is the variance ratio test that focuses attention on the uncorrelated residuals, is widely used for examining the behaviour of series that are not normally distributed and is shown to have good size and power properties (Chow and Denning 1993). Chow and Denning's (1993) multiple variance ratio (MVR) procedure detailed below is based on Lo and MacKinlay's (1988) variance ratio test with the size of the test controlled for multiple comparisons [for previous applications see Huang (1995), Smith (2002) and Smith et al. (2002)].

As shown by Lo and Mackinlay (1988), the variance ratio statistic is derived from the assumption of linear relations in observation interval regarding the variance of increments. If a time series follows a random walk process, the variance of a q th-differenced variable is q times as large as the first-differenced variable. For a time series partitioned into equally spaced intervals and characterised by random walks, one q th of the variance of $(p_t - p_{t-q})$ is expected to be the same as the variance of $(p_t - p_{t-1})$:

$$Var(p_t - p_{t-q}) = qVar(p_t - p_{t-1}) \quad (3)$$

where q is any positive integer. The variance ratio is then denoted by:

$$VR(q) = \frac{\frac{1}{q}Var(p_t - p_{t-q})}{Var(p_t - p_{t-1})} = \frac{\sigma^2(q)}{\sigma^2(1)} \quad (4)$$

such that under the null hypothesis $VR(q) = 1$. For a sample size of $nq + 1$ observations $(p_0, p_1, \dots, p_{nq})$, Lo and Mackinlay's (1988) unbiased estimates of $\sigma^2(1)$ and $\sigma^2(q)$ are computationally denoted by:

$$\hat{\sigma}^2(1) = \frac{\sum_{k=1}^{nq} (p_k - p_{k-1} - \hat{\mu})^2}{(nq - 1)} \quad (5)$$

and

$$\hat{\sigma}^2(q) = \frac{\sum_{k=q}^{nq} (p_k - p_{k-q} - q\hat{\mu})^2}{h} \quad (6)$$

where $\hat{\mu}$ = sample mean of $(p_t - p_{t-1})$ and:

$$h \equiv q(nq + 1 - q)(1 - \frac{q}{nq}) \quad (7)$$

Lo and Mackinlay (1988) produce two test statistics, $Z(q)$ and $Z^*(q)$, under the null hypothesis of homoskedastic increments random walk and heteoskedastic increments random walk respectively. If the null hypothesis is true, the associated test statistic has an asymptotic standard normal distribution. With a sample size of $nq + 1$ observations $(p_0, p_1, \dots, p_{nq})$ and under the null hypothesis of homoskedastic increments random walk, the standard normal test statistic $Z(q)$ is:

$$Z(q) = \frac{V\hat{R}(q) - 1}{\hat{\sigma}_0(q)} \quad (8)$$

where

$$\hat{\sigma}_0(q) = \left[\frac{2(2q-1)(q-1)}{3q(nq)} \right]^{1/2} \quad (9)$$

The test statistic for a heteoskedastic increments random walk, $Z^*(q)$ is:

$$Z^*(q) = \frac{V\hat{R}(q) - 1}{\hat{\sigma}_e(q)} \quad (10)$$

where

$$\hat{\sigma}_e(q) = \left[4 \sum_{k=1}^{q-1} \left(1 - \frac{k}{q} \right)^2 \hat{\delta}_k \right]^{1/2} \quad (11)$$

and

$$\hat{\delta}_k = \frac{\sum_{j=(k+1)}^{nq} (p_j - p_{j-1} - \hat{\mu})^2 (p_{j-k} - p_{j-k-1} - \hat{\mu})^2}{\left[\sum_{j=1}^{nq} (p_j - p_{j-1} - \hat{\mu})^2 \right]^2} \quad (12)$$

Lo and MacKinlay's (1988) procedure is devised to test individual variance ratios for a specific aggregation interval, q , but the random walk hypothesis requires that $VR(q) = 1$ for all q . Chow and Denning's (1993) multiple variance ratio (MVR) test generates a procedure for the multiple comparison of the set of variance ratio estimates with unity. For a single variance ratio test, under the null hypothesis, $VR(q) = 1$, hence $M_r(q) = VR(q) - 1 = 0$. Consider a set of m variance ratio tests $\{M_r(q_i) \mid i = 1, 2, \dots, m\}$. Under the random walk null hypothesis, there are multiple sub-hypotheses:

$$\begin{aligned}
H_{oi}: & \quad M_r(q_i) = 0 & \text{for } i = 1, 2, \dots, m \\
H_{li}: & \quad M_r(q_i) \neq 0 & \text{for any } i = 1, 2, \dots, m
\end{aligned} \tag{13}$$

The rejection of any one or more H_{oi} rejects the random walk null hypothesis. For a set of test statistics, say $Z(q)$, $\{Z(q_i) \mid i = 1, 2, \dots, m\}$, the random walk null hypothesis is rejected if any one of the estimated variance ratio is significantly different from one. Hence only the maximum absolute value in the set of test statistics is considered. The core of the Chow and Denning's (1993) MVR test is based on the result:

$$PR\{\max(|Z(q_1)|, \dots, |Z(q_m)|) \leq SMM(\alpha; m; T)\} \geq 1 - \alpha \tag{14}$$

where $SMM(\alpha; m; T)$ is the upper α point of the Standardized Maximum Modulus (*SMM*) distribution with parameters m (number of variance ratios) and T (sample size) degrees of freedom. Asymptotically when T approaches infinity:

$$\lim_{T \rightarrow \infty} SMM(\alpha; m; \infty) = Z_{\alpha^*/2} \tag{15}$$

where $Z_{\alpha^*/2}$ = standard normal distribution and $\alpha^* = 1 - (1 - \alpha)^{1/m}$. Chow and Denning control the size of the *MVR* test by comparing the calculated values of the standardized test statistics, either $Z(q)$ or $Z^*(q)$ with the *SMM* critical values. If the maximum absolute value of, say $Z(q)$ is greater than the *SMM* critical value than the random walk hypothesis is rejected.

Importantly, the rejection of the random walk under homoskedasticity could result from either heteroskedasticity and/or autocorrelation in the electricity spot price series. If the heteroskedastic random walk is rejected than there is evidence of autocorrelation in the spot electricity price series. With the presence of autocorrelation in the price series, the first order autocorrelation coefficient can be estimated using the result that $\hat{M}_r(q)$ is asymptotically equal to a weighted sum of autocorrelation coefficient estimates with weights declining arithmetically:

$$\hat{M}_r(q) = 2 \sum_{k=1}^{q-1} \left(1 - \frac{k}{q}\right) \hat{\rho}(k) \tag{16}$$

where $q = 2$

$$\hat{M}_r(2) \equiv V\hat{R}(2) - 1 = \hat{\rho}(1) \tag{17}$$

V. EMPIRICAL RESULTS

Table 3 presents the results of the multiple variance ratio tests of the four state-based spot electricity markets; namely, New South Wales (NSW), Victoria (VIC), Queensland (QLD) and South Australia (SA). Different sampling periods are employed for the peak and off-peak period price series that take into the differing structures of the underlying data, i.e. Monday to Friday for the peak period (5-day cycle) and Sunday to Saturday for the off-peak period (7-day cycle). The sampling intervals for the peak period are 2, 5, 10 and 15 days, while the sampling intervals for the off-peak period are 2, 7, 14 and 21 days.

For each interval Table 3 presents the estimates of the variance ratio $VR(q)$ and the test statistics for the null hypotheses of homoskedastic, $Z(q)$ and heteroskedastic, $Z^*(q)$ increments random walk. Under the multiple variance ratio procedure, only the maximum absolute values of the test statistics are examined. For a sample size of 522 and 731 for the peak and off-peak periods respectively and $m = 4$, the critical value is 2.49 at the 0.05 level of significance. For each set of multiple variance ratio tests, an asterisk denotes the maximum absolute value of the test statistic that exceeds this critical value and thereby indicates whether the null hypothesis of a random walk is rejected.

Table 3. Multiple variance ratio tests for peak and off-peak spot prices in Australian regional markets, 1999-2001

Region	Statistics	Peak period prices				Off-peak period prices			
		q = 2	q = 5	q = 10	q = 15	q = 2	q = 7	q = 14	q = 21
NSW	VR(q)	0.8676	0.4167	0.2566	0.1840	0.8527	0.3064	0.1816	0.1554
	Z(q)	3.0214	*6.0767	5.0258	4.3844	3.9810	*6.8753	5.4087	4.4726
	Z*(q)	1.4648	*3.3552	3.0128	2.7547	1.4335	*2.9546	2.8913	2.7127
VIC	VR(q)	0.5022	0.2854	0.1569	0.1179	0.9295	0.3217	0.1814	0.1468
	Z(q)	*11.3628	7.4452	5.6994	4.7398	1.9050	*6.7239	5.4100	4.5179
	Z*(q)	*4.5334	3.5833	3.1862	2.8979	1.0475	2.2205	2.1888	2.0752
QLD	VR(q)	0.6161	0.2997	0.1280	0.1054	0.7363	0.2577	0.1619	0.1200
	Z(q)	*8.7636	7.2958	5.8948	4.8069	7.1250	*7.3588	5.5387	4.6602
	Z*(q)	*5.4688	5.2875	4.7609	4.0938	2.3125	*3.0355	2.7272	2.5687
SA	VR(q)	0.4854	0.2461	0.1162	0.0802	0.6877	0.2302	0.1077	0.0808
	Z(q)	*11.7455	7.8545	5.9748	4.9424	*8.4371	7.6313	5.8972	4.8677
	Z*(q)	*5.4337	4.3054	3.7847	3.4311	3.6715	*3.8902	3.6411	3.3301

Notes: Peak period encompasses Mondays to Fridays 7:00 to 21:00, off-peak period encompasses Monday to Fridays before 7:00 and after 21:00 plus Saturday and Sunday; NSW–New South Wales, VIC–Victoria, QLD–Queensland, SA–South Australia; VR(q) – variance ratio estimate, Z(q) - test statistic for null hypothesis of homoskedastic increments random walk, Z* (q) - test statistic for null hypothesis of heteroskedastic increments random walk; the critical value for Z(q) and Z*(q) at the 5 percent level of significance is 2.49, asterisk indicates significance at this level; Sampling intervals (q) are in days.

Consider the results for NSW in the peak period. The null hypothesis that the natural logarithm of the spot electricity price series follows a homoskedastic random walk is rejected at $Z(5) = 6.0767$. Rejection of the null hypothesis of a random walk under homoskedasticity for a 5-day period is also a test of the null hypothesis of a homoskedastic random walk under the alternative sampling periods and we may therefore conclude that NSW peak period spot electricity prices do not follow a random walk. However, rejection of the null hypothesis under homoskedasticity could result from heteroskedasticity and/or autocorrelation in the price series. After allowing for generalized heteroskedasticity, the null hypothesis is also rejected at $Z^*(5) = 3.3552$. The heteroskedastic random walk hypothesis is thus rejected because of autocorrelation in the daily increments of the natural logarithm of NSW spot electricity prices. We may conclude that the NSW peak-period electricity spot market is not informationally efficient.

Further, Lo and Mackinlay (1988) show that for $q=2$, estimates of the variance ratio minus one and the first-order autocorrelation coefficient estimator of daily price changes are asymptotically equal. On this basis, the estimated first order autocorrelation coefficient is -0.1324 corresponding to the estimated variance ratio $\hat{VR}(2)$ of 0.8676 (i.e. $0.8676 - 1.0000$). This indicates there is negative autocorrelation in NSW peak-period electricity spot prices. Just one implication is that a relatively simple stochastic model incorporating an autoregressive process could model the short-term fluctuations in NSW peak period electricity prices. Alternatively, had the heteroskedastic random walk hypothesis not been rejected then models that take account of varying heteroskedasticity, such as the autoregressive conditional heteroskedasticity (ARCH) family of techniques, would be required.

Similar results are obtained for VIC, QLD and SA in peak period electricity prices. These markets all reject both homoskedastic and heteroskedastic increments random walk hypotheses because of negative autocorrelation in the series. The estimated first order-autocorrelation coefficients range from -0.3839 for QLD to -0.5146 for SA. This would suggest that a simple first-order autoregressive model used to forecast prices in electricity markets could potentially be more accurate for South Australia, followed by Victoria, Queensland and New South Wales.

In the off-peak period, the NSW, QLD and SA markets also reject both homoskedastic and heteroskedastic increments random walk hypotheses because of negative autocorrelation in the series. The estimated first order autocorrelation coefficients in this instance are -0.1473

for NSW, -0.2637 in Queensland and -0.3123 for South Australia. Once again first-order autoregressive modelling techniques may yield useful forecasts of electricity prices, and would be relatively more accurate for South Australia than the remaining states. As a rule, the autocorrelation coefficients in the off-peak period are lower than in the peak period. More interestingly, however, the Victorian off-peak period price series rejects the homoskedastic increments random walk hypothesis but fails to reject the heteroskedastic increments random walk hypothesis. This could be the result of heteroskedasticity and/or autocorrelation in the VIC electricity spot price series. The suggestion is that the Victorian off-peak period electricity prices follow a random walk and are therefore informationally efficient.

The finding that electricity prices in most of the National Electricity Market's (NEM) regional markets do not follow a random walk is not difficult to rationalise. That is, it would normally be only in large, institutionally mature, liquid markets that there would be a sufficiently active price formation process for the market to follow a random walk. By way of contrast, the Australian electricity markets have a very small number of participants that are generally able to exert market power and trading rules that may serve to structure price formation. For example, the recent ABARE (2002) paper concerning competition in the Australian electricity market found that "in the six months examined in 1999, prices were considered to have deviated substantially from competitive outcomes for at least two-thirds of the period in all states...". However, the result that Victorian off-peak period electricity prices do in fact follow a random walk is more difficult to justify. Certainly, the Victorian market was the first to commence competitive trading in 1994 and it benefits from relatively more transmission interconnectors than the other regions. Combined together, this would suggest that in the off-peak period when transmission constraints are less pronounced that market power is constrained and the price formation process more closely approximates a random walk.

VI. CONCLUDING REMARKS

This paper examines the informational efficiency of four Australian electricity spot markets during the period 1999 to 2001. All of these spot markets are member jurisdictions of the recently established National Electricity Market (NEM). Multiple variance test statistics with both homoskedastic and heteroskedastic variances are used to test for random walks in both peak and off-peak period prices. The results indicate that despite the presence of a national market for electricity, only the Victorian off-peak period market is informationally

efficient. This would suggest, amongst other things, that Australian spot electricity prices could be usefully forecasted using autoregressive-modelling techniques, especially in South Australia and Queensland. The evidence also provides complementary evidence to the results of studies concerned with the economic efficiency of these liberalised markets that generators with market power may be sustaining non-competitive outcomes.

This analysis could be extended in a number of ways. One useful extension would be to examine each of the electricity markets individually and in more detail. For example, wholesale electricity spot markets in Victoria and New South Wales have existed since 1994 and 1996 respectively and an examination of the price formation process in these states would be particularly useful. Another extension would be to consider market power in an alternative form where generators with market power may have an incentive to create volatility in the spot market and not just increase prices by withholding capacity or offering higher prices.

REFERENCES

- Asher, A. (1998). Fair competition in the electricity and gas markets. In *National Power Sourcebook 1999*. AIC Worldwide Pty Ltd, Sydney, 10–17.
- Australian Bureau of Agricultural and Resource Economics (ABARE) (2002) *Competition in the Australian National Electricity Market*, ABARE Current Issues 1655, January.
- Australian Competition and Consumer Commission (2000). *Infrastructure Industries: Energy*, Commonwealth of Australia, Canberra.
- Brennan, D. & Melanie, J. (1998). Market power in the Australian power market, *Energy Economics*, 20(2), 121–133.
- Chow, K.V. and Denning, K. (1993) A simple multiple variance ratio test, *Journal of Econometrics*, 58(3), 385–401.
- Crow, R.T. (2002) What works and what does not in restructuring electricity markets, *Business Economics*, July, 41–56.
- De Vany, A.S. and Walls, W.D. (1999) Cointegration analysis of spot electricity prices: insights on transmission efficiency in the western US, *Energy Economics*, 21(3), 435–448.
- Huang, B.N. (1995) Do Asian stock markets follow random walks? Evidence from the variance ratio test, *Applied Financial Economics*, 5(4), 251–256.
- International Energy Agency (2001). *Energy Policies of IEA Countries: Australia 2001 Review*, Organisation for Economic Cooperation and Development (OECD), Paris.
- Joskow, P.L. and Kahn, E. (2001) *A quantitative analysis of pricing behaviour in California's wholesale electricity market during summer 2000*, National Bureau of Energy Research, Working Paper 8157.
- Lo, A. and MacKinlay, A.C. (1988) Stock market prices do not follow random walks: Evidence from a simple specification test, *Review of Financial Studies*, 1(), 41–66.
- Lucia, J.J. and Schwartz, E.S. (2001). *Electricity Prices and Power Derivatives: Evidence for the Nordic Power Exchange*. University of California Los Angeles Working Paper, Los Angeles.
- National Electricity Market Management Company Limited (2001). *An Introduction to Australia's National Electricity Market*, NEMMCO, Melbourne.
- National Electricity Market Management Company Limited (2002). WWW site: <<http://www.nemmco.com.au/>>. Accessed October 2002.
- Robinson, T. (2000) Electricity pool series: a case study in non-linear time series modeling. *Applied Economics*, 32(5), 527–532.

- Robinson, T. and Baniak, A. (2002) The volatility of prices in the English and Welsh electricity pool, *Applied Economics* 34, 1487-1495.
- Smith, G. (2002) Tests of random walk hypothesis for London gold prices, *Applied Economics Letters*, 9(5), 671-674.
- Smith, G., Jefferis, K. and Ryoo, H.J. (2002) African stock markets: multiple variance ratio tests of random walk, *Applied Financial Economics*, 12(4), 475-484.
- Wolfram, C.D. (1999) Measuring duopoly power in the British electricity spot market, *American Economic Review*, 89(4), 805-826.